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16. Abstract

This report discusses the influence of adhesion strength on destruction of composite material during stretching and proposes a much simpler method of finding the parameters that influence the strength and destruction of the composite. The proposed model makes it possible to calculate the critical strength that can be realized in the composite during bending or stretching.

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SCALAR EFFECT OF FIBER STRENGTH AND PROPERTIES OF UNIDIRECTIONAL COMPOSITES BASED ON THEM

Yu. G. Korabel'nikov, V. P. Tamuzh, O. F. Siluyanov, V. M. Bondarenko, M. T. Azarova

A characteristic feature of fibers used as reinforcing /195* fillers for composite materials is the scalar effect of strength, i.e., the dependence of strength on the gripping strength. For carbon fibers this property has been analyzed in detail in [1] and it has been shown that at each gripping length, the distribution of strength is satisfactorily approximated by the Weibull distribution, although there is a noticeable definite polymodality. The average values of the strength distribution curves inddouble logarithmic coordinates depend linearly on the gripping length of the fiber.

It was also demonstrated that the strength of the composite depends on the strength of the fibers on the so-called ineffective length equal to several dozen diameters of fibers, and before complete destruction in the sample , only several percentages (P%) of the total number of "ineffective lengths" of fibers in the composite are torn. P was experimentally determined by a cumbersome calculation of the lengths of torn fibers after destruction of the composite. Theoretical calculation ignored the finite value of shear strength between the fiber and the matrix, and assumed in the calculation of ineffective length that adhesion on the interface in the vicinity of the rupture is not disrupted.

This report discusses the influence of adhesion strength on destruction of composite material during stretching and proposes a considerably simpler method of finding the parameters that influence the strength and destruction of the composite.

The linear dependence of average strength of fibers on gripping length l is expressed in the form

*Numbers in right margin indicate pagination in original text.

$$\lg \langle \sigma_n \rangle = A - B \lg \frac{l}{l_0}, \qquad (1)$$

where A, B and l_0 = 1 mm are constant quantities, and insofar as with the Weibull distribution

$$F(\sigma) = 1 - \exp\left[- \frac{l}{l_0} \left(\frac{\sigma}{\sigma_0} \right)^{\beta} \right]$$

the average strength looks like

$$\langle \sigma_n \rangle = \sigma_0 \left(\frac{l}{l_0} \right)^{-\frac{1}{\beta}} \Gamma \left(1 + \frac{1}{\beta} \right), \qquad (2)$$

then, consequently,

$$B = \frac{1}{\beta}; \quad A = \lg \sigma_0 + 1/\beta \lg l_0 + \lg \Gamma(1 + 1/\beta).$$

The composite can be destroyed because of the development of a main fracture in the area of the microdefect, separation into layers on the fiber - matrix interface or by sequential splitting of the fibers of the reinforcing filler into shorter segments. The mechanism of splitting was confirmed experimentally for unidirectional composites with up to 65 - 70% volume of filler. /196

We will discuss the mechanism for splitting of fibers in the composite in more detail. Under the influence of normal stretching stresses, the reinforcing fibers tear in places containing the most dangerous surface defects. On the surface of the formed fragments of the fibers there may only be defects which are less dangerous than those on which destruction has already occurred. This destruction of the fibers in the composite distinguishes them from tests at different gripping lengths in which the decrease is length only reduces the probability of the existence of dangerous defects, but does not exclude this possibility. Distributions of strengths of fibers in tests at different gripping lengths and their splitting in a composite

could be distinguished and approximation of the Weibull distribution in this case is a known assumption.

As the fibers are split in the composite, their strength rises, and until the fibers interact with each other, they are capable of absorbing a load. When the length of the fragments of fibers diminishes so much that the shear stresses between the fiber and the matrix exceed the shear strength, splitting of fibers ceases and the fragments will be pulled out of the matrix.

The critical (or ineffective) length of the fiber l_{kp} without consideration for the influence of adhesion is determined by the Rozen formula [2], but if we assume that the shear stresses between the fiber and the matrix cannot be greater than the shear strength τ, then the critical length can be obtained approximately from the expression

$$l_{kp}=\frac{\langle\sigma_в\rangle(l_{kp})d_в}{2\tau}, \qquad (3)$$

where d_B is the diameter of the fiber; $\langle\sigma_в\rangle(l_{kp})$ is the average strength of the fiber at length l_{kp} [3]. Formula (4) assumes a uniform distribution of tangential stress on the fiber surface. Insofar as the fibers of the reinforcing fillter in the composite cannot be torn into fragments whose length would be less than l_{kp}, then the fiber strength at critical length in the next statement will be called the critical realizable strength, $\sigma_{кр}$. In evaluating the quality of the composite material, it is apparently necessary to compare the strength realized in it with value $\sigma_{кр}$.

Publication [4] has suggested a graph analytical method for evaluating the strength of fibers at critical length which takes into consideration the nature of the epures of normal stresses in the fiber - matrix system and the existence of a scalar relationship of the fiber strength. Without doubting the expediency of considering all factors influencing strength, for an

approximate evaluation of the critical realizable strength of the filler fibers, we consider it sufficient to solve the sytem of equations (1) and (3) extrapolated for l_{kp}, from which

$$\lg \sigma_{np} = \frac{1}{1+B}(A - B \lg d_в + B \lg 2\tau) \qquad (4)$$

and

$$\lg l_{kp} = \frac{1}{1+B}(A + \lg d_в - \lg 2\tau). \qquad (5)$$

Equations (4) and (5) link the quantity σ_{np} and the critical length with the constants A and B of the scalar relationship of fiber strength, their diameter and adhesion to the matrix expressed as shear strength.*

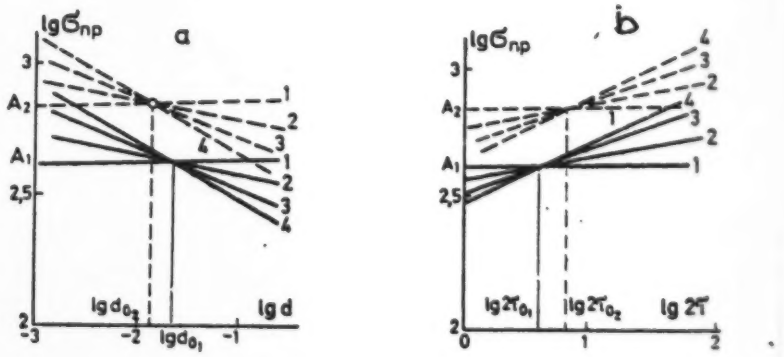

Figure 1. Dependences of Critical Realizable Strength on Diameter of Filler Fibers (a) and on Adhesion of Fibers to Matrix (b) for B = 0 (1); 0.1 (2), 0.2 (3), 0.3 (4); (_____) A_1 = 2.621; (----) A_2 = 2.846; d_B = 0.01 mm.

Figure 1 presents the dependences of σ_{np} on the diameter of the fiber and adhesion calculated for some values of the coefficients A and B. It follows from the graphs that the critical /197

* It is assumed here that l_0 is single length and $\lg l_0 = 0$. One can, of course, include in these relationships the characteristic strength and size, and switch to dimensionless quantities, but the essence does not change and specific dimensional numbers of obtained in the measurements.

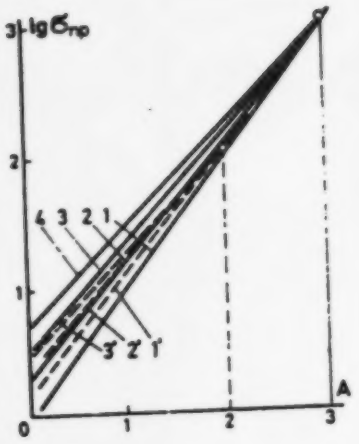

Figure 2. Dependences of Critical Realizable Strength on A for B = 0 (1), 0.1 (2), 0.2 (3), 0.3 (4). $\tau_{изв}$ = 5 kg-f/mm^2; the lines correspond to d_B = 0.01 (_____) and 0.1 mm (---)

realizable strength increases with a rise in B = 1/β (i.e., with an increase in the spread of strength) for thin fibers with good adhesion to the matrix and diminishes for fibers with large diameter and poor adhesion. The different influence of the coefficient B on the critical realizable strength for filler fibers with large and small diameter makes it possible to explain the results presented in [5], where increase in the coefficient of variation in strength of the fibers 8 - 10 μm in diameter was accompanied by an increase in the strength of the composite. It is easy to note that with

$$\lg d_B = \lg . \qquad (6)$$

the right side of (4) does not depend on the parameter of the spread of B, i.e., formula (6) determines the abscissa of the intersection point of the straight lines in fig. 1. The quantity A is a logarithm for the average strength of fibers on a single gripping length, while formula (6) shows the value of diameter and adhesion from which the change in parameter B increases or decreases the critical realizable strength of the composite.

The dependences of critical and realizable strength on A are shown in fig. 2. For fibers with diameter 10 μm and τ = 5 kg-f/mm^2, with an increase in the coefficient β, the critical realizable strength rises to values A = 3. For fibers with diameter 100 μm with A > 2, decrease in $\sigma_{пр}$ accompanies the increase in B. Thus, the critical realizable strength of the fiber depends significantly on the coefficient A of the scalar relationship of the fiber strength. The influence of the coefficient B varies for thin and thick fibers and depends on their adhesion to the matrix.

However, as indicated in the beginning of the article and in [1], the critical possible strength is never reached in the composite because with lower stresses , splitting of the fibers in the composite results in the development of a main fracture. In order to predict the properties of the real composites, it is necessary to know the magnitude of the coefficient of realization k: $\sigma_р = k\sigma_{пр}$, where $\sigma_р$ is the strength of the fiber realized in the composite. The quantity k depends, of course, on the coefficient of reinforcement, the size of the sample, the manufacturing technology, testing conditions, etc. But essentially k is determined by the fact that by the moment of destruction of the composite it will not have accumulated fiber ruptures in a quantity equal to half of all the critical lengths (as assumed for $\sigma_{пр}$), but only P% of the quantity of critical lengths in the sample. According to (1) /198

$$\sigma(P) = \sigma_0 \left[-\frac{l_0}{l} \ln(1 - P/100) \right]^{1/\beta},$$

and with P/100 << 1

$$\sigma(P) \approx \sigma_0 \left(\frac{l_0}{l} \right)^{1/\beta} (P/100)^{1/\beta}. \qquad (7)$$

Consequently, we obtained from (2) and (7)

$$k \approx \frac{(P/100)^{1/\beta}}{\Gamma(1+1/\beta)} = \frac{(P/100)^{B}}{\Gamma(1+B)}. \qquad (8)$$

For $\beta = 6$ (B = 0.167) we have with P = 10% k = 0.73 with 5% 0.65, with 3% 0.6, which agrees completely with the experimentally observed quantities.

Equation (4) for the critical realizable strength can be written in the form

$$\lg \sigma_p - \lg k = \frac{1}{1+B}(A - B \lg d_B + B \lg 2\tau).$$

Thus, in order to predict the strength of the composite based on a specific fibrous filler with different matrices and different activation of the fiber surface, it is sufficient to know the quantities A, B, d_B and k. In order to determine these constants, one can use one of the methods presented below.

1. Based on tests on fibers at different gripping lengths we define A and B. The diameter of the fiber d_B is measured directly. After testing the composite based on a specific fibrous filler for stretching (or bending) and for shear in order to determine τ we compare the realized strength with the critical obtained from equation (4) and find the quantity k. Now we have all the necessary data for predicting the realized strength with different values τ.

2. By another method to evaluate A, B and k no tests are required for the fibers at different gripping lengths and construction of a scalar relationship of the fiber strength. It is reduced to determining the average strength of the fiber at some one length (for example, on base 10 mm) and tests for stretching (or bending) and shear of two composites with different τ (change in adhesion to the matrix can be attained by activating the surface of the fiber or changing the binding agent). By using the data of these tests we compile the following equations:

$$\lg \langle \sigma_{10} \rangle = A - B; \quad \lg \sigma_{p1} - \lg k = \frac{1}{1+B}(A - B \lg d_B + B \lg 2\tau_1);$$

$$\lg \sigma_{p2} - \lg k = \frac{1}{1+B}(A - B \lg d_B + B \lg 2\tau_2).$$

After solving these equations for A, B and k we use their values for forecasting.

As an example we compute A, B and k by using the data presented in the table. After substituting the tabular data and after solving equations, we obtain: for high-strength filler A_p = 2.6862; B_p = 0.225 and k = 0.561; for high-modular filler Ap = 2.5202, Bp = 0.0793 and k = 0.69. The experimental values /199
of the constants A and B for high-strength and high-modular fillers are respectively equal to 2.656 and 0.188; 2.516 and 0.079.

CARBON FIBER BRAIDED FILLER

(a) Тип наполнителя	(b) Вид углеродного волокна	$(\sigma_в)_{изг}$ (c) при $l=10$ мм, кгс/мм² (d)	(e) Диаметр волокна, мм	(f) Свойства композитов		
				$V_в$, %	$\sigma_{в.н}$, кгс/мм (d)	$\tau_{сдв}$, кгс/мм (d)
(g) Высокопрочное волокно	Исходное (h)	289	0,0081	56,1	162,2	2,72
	Активированное (i)	291	0,0081	60,0	206,6	7,07
(j) Высокомодульное волокно	Исходное (k)	276	0,0075	52,6	123,6	1,84
	Активированное (l)	278	0,0075	59,0	151,4	6,21

Key:
a. Type of filler
b. Type of carbon fiber
c. at
d. kg-f/mm^2
e. diameter of fiber, mm
f. Properties of composites
g. High-strength fiber
h. Original
i. Activated
j. High-modular fiber

For different values τ we use these data to calculate the realized strength in bending (fig. 3). As is apparent from the graphs, the experimental points corresponding to strength in bending and shear of the composites based on fillers with different types of surface activation are grouped near the calculated relationships and the maximum error does not exceed 10 - 12%. Figure 4 presents the scalar relationships of strength

of high-strength and high-modular carbon fibers constructed from data of tests at different lengths and using the constants A and B computed above. Taking into consideration the approximateness of the proposed evaluation method, the obtained coincidence should be considered good.

A feature which deserves attention is the decrease in the value of the coefficient of realization k with a rise in the

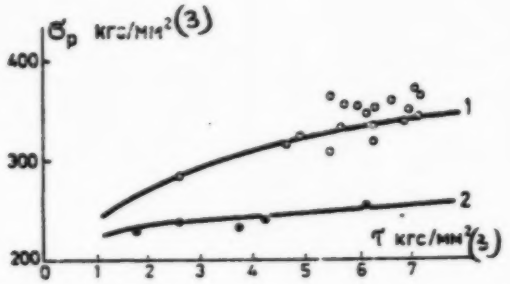

Figure 3. Dependences of Strength in Composite for Bending for High-Strength (1) and High-modular (2) Carbon Fibers

Key:

_____ calculation

Calculated Values: $A_1 = 2.6862$; $B_1 = 0.225$; $k_1 = 0.561$; $A_2 = 2.502$; $B_2 = 0.0793$; $k_2 = 0.69$.

3. $kg\text{-}f/mm^2$

tangent of the angle of inclination of the scalar relationship of the fiber strength, i.e., B. One of the possible reasons for this link could be the break in the scalar relationship in the area of small gripping lengths, i.e., the unreliability of the rectilinear extrapolation to $l = l_{kp}$. Another possible reason could be the appearance onthe surface of the fiber of a brittle shell that emerges in some technological conversions [5]. Cracking of this shell when a definite level of deformations is reached in the filler fibers excludes the increase in fiber strength when they are split in the composite. Consequently, strength of the split fibers is lower than that evaluated by

extrapolating the scalar relationship of fiber strength to the corresponding critical lengths. It is natural that the actual strength realized in the composite will differ more from the maximum realizable (k is lower) the steeper the scalar relationship of fiber strength, i.e., the higher the coefficient B. And finally, increase in B = 1/β means corresponding increase in the spread of strength. In this case, if the critical level of splitting remains approximately constant, then as is apparent from (8), k must diminish with an increase in B.

It should be noted that in this work, description of the scalar effect of fiber strength is made using the Weibull distribution which is a known approximation and results in non-contradictory results. The next approximation is a more complex polymodal distribution which will be discussed in subsequent works. /200

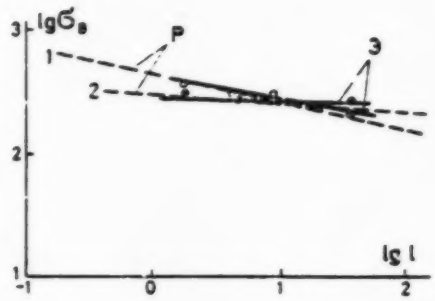

Figure 4. Dependences of Strength of High-Strength (1) and High-Modular (2) Carbon Fibers on Gripping Length. P--calculation; ϑ --experiment

In the opinion of the authors, this method can be useful from the viewpoint of a more objective evaluation of the realization of the fiber properties in a composite, since it is based on a model which takes into consideration adhesion of the fiber to the matrix. In this case, all the factors included in the

calculated formulas are determined by simple and known techniques.

CONCLUSIONS

1. A critical model of destruction of composites based on fibrous filler with scalar effect of strength is examined, and a scheme is given for computing the realization of the properties of the filler which make it possible to distinguish the influence of the fiber diameter, its scalar effect (constants A and B) and adhesion to the matrix.

2. It was established that decrease in the fiber diameter in the filler, increase in their adhesion to the matrix and constant A result in a growth of the critically attainable strength of the composite. In this case for fibers with small diameters and high adhesion to the matrix, a growth is observed in the critical strength of the composite with an increase in the spread of fiber strength and the scalar effect.

3. For fibers with large diameter and low adhesion, increase in the spread of strength and correspondingly the scalar effect results in a decrease in the critical strength of the composite. An equation was obtained which makes it possible to determine the diameter d_B and adhesion τ in which the critical strength of the composite does not depend on the scalar effect of the fiber strength.

4. The proposed model makes it possible with a certain scalar effect of filler strength to calculate the critical strength that can be realized in the composite during bending or stretching; from the results of testing the composites, the scalar effect of filler strength and the coefficient of realization of the critical strength can be evaluated.

5. A good agreement was obtained of the results of the experiment and calculation made by two techniques for composites with high-strength and high-modular carbon fiber fillers.

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